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Integrating TQM and Lean Manufacturing for Sustainable Operational Efficiency in Digitalized Manufacturing Industries

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Abstract. *This study investigates the integration of Total Quality Management (TQM) and Lean Manufacturing (LM) to enhance sustainable operational efficiency in digitalized manufacturing industries. Partial Least Squares Structural Equation Modeling (PLS-SEM) approach was employed to empirically examine the relationship between TQM, LM, digital transformation, operational efficiency, and sustainability performance. Data were collected from 198 managers and supervisors in Indonesian manufacturing firms that have adopted digital technologies. The results reveal that both TQM and LM significantly contribute to operational efficiency, while digital transformation strengthens the synergy between them. Furthermore, operational efficiency positively impacts sustainability performance, demonstrating that efficiency improvements align with sustainability goals. The findings provide theoretical contributions by presenting an integrated framework of TQM Lean Digitalization Sustainability, and practical implications for manufacturing managers seeking to achieve operational excellence in the Industry 4.0 era.*

Keywords: *total quality management, lean manufacturing, digital transformation, operational effiency, suistainability, PLS-SEM*

I. INTRODUCTION

Global manufacturing industries are facing increasing pressure to enhance efficiency, reduce waste, and align operations with sustainability goals. The customer has very diverse demands in Industry 4.0 era and manufacturer is expected to have high production flexibility to satisfy those demands(Setiawan & Sitepu, 2019). Digital transformation has accelerated these challenges by introducing technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics and digital twin that reshape manufacturing processes. In this context, Total Quality Management (TQM) and Lean Manufacturing (LM) have emerged as two essential approaches for driving operational excellence.

In this study, TQM and LM are two important approaches that have been proven to improve the performance of the manufacturing industry. TQM is a comprehensive strategy that emphasizes the involvement of all organizational members in continuous improvement, with a philosophy of preventing errors from the outset, thereby enhancing quality, innovation, and long-term organizational performance sustainability (Wassan, Memon, Mari, & Kalwar, 2022). Meanwhile, LM serves as a management philosophy rooted in the Toyota Production System, emphasizing simplification, standardization, and continuous improvement to eliminate waste and inefficiencies, thereby enhancing overall organizational performance through the optimal use of time, money, and resources(Driouach, Zarbane, & Beidouri, 2023). Both share the same goal, namely achieving sustainable operational efficiency.

Although many studies have discussed TQM and LM separately, the integration of the two has rarely been explored in depth, especially in the context of industrial digitalization. Meanwhile LM is referred to as a combination of best practices that improves the overall efficiency, effectiveness, and productivity of an industry(Elemure, Dhakal, Leseure, & Radulovic, 2023). Several studies

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present integrative frameworks that combine TQM elements (quality policies, statistical tools, improvement culture) with Lean practices (5S, kaizen, JIT) and digital enablers (IIoT, analytics, digital twin). These frameworks emphasize three layers: (1) people & culture (skills, leadership), (2) process & methods (digital-enabled Lean/TQM tools), and (3) technology & data (IIoT infrastructure, analytics platforms). Successful implementation requires balancing these layers and adopting a phased approach (piloting scaling)(Komkowski, Antony, Garza-Reyes, Tortorella, & Pongboonchai-Empl, 2023). However, without integration, the two have the potential to operate separately, preventing the achievement of optimal benefits.

Manufacturing companies face challenges in measuring the actual impact of integrating TQM and Lean on operational efficiency in the digital era. The Industry 4.0 (I4.0) era presents new opportunities to integrate TQM and LM. According to McKinsey & Company, their survey explored 28 digital use cases ranging from demand forecasting and capacity planning to warehouse automation and asset maintenance, including around a dozen generative AI applications that leverage large language models and related technologies to automate tasks such as scenario analysis and documentation generation(Li, Gosling, & Srivastava, 2024). Thus, TQM and LM can strengthen their synergy and generate operational efficiency that is not only faster and more cost-effective but also sustainable.

Most of the previous studies are still limited to case studies or descriptive approaches, thus providing fewer empirical models that can be tested quantitatively. Despite providing valuable insights, this study is limited to a descriptive analytical approach and simple regression within a single-case context, thereby restricting the development of a comprehensive empirical model that can be quantitatively validated and generalized, particularly in examining the complex interplay between TQM, innovation performance, and human resource efficiency(Hongsakul, Sirisombat, & Subongkod, 2025). Moreover, this study remains constrained to the analysis of cause effect relationships among Lean practices through the fuzzy DEMATEL method, which restricts its ability to establish a robust empirical model that could be quantitatively tested and generalized to explain environmental performance improvement across diverse manufacturing sectors(Ferrazzi, Costa, Frecassetti, & Portioli-Staudacher, 2025).

To address this gap, future research should employ longitudinal and quantitative methodologie particularly Partial Least Squares Structural Equation Modelling (PLS-SEM) or similar advanced modeling techniquesto empirically validate the integration of Quality 4.0, Lean digitalization, and sustainability indicators. Practical implications include the adoption of digital value stream mapping, the implementation of pilot projects in critical production lines, and the strengthening of internal analytics capabilities(Costa, Alemsan, Bilancia, Tortorella, & Portioli Staudacher, 2024). PLS-SEM is beneficial for managing foundational constructs, a characteristic pertinent to this study's emphasis on the important success aspects of TQM, which may lack shared indications but together influence TQM results(Alawag et al., 2025). TQM is a holistic methodology towards the general change of an organization, the theory of TQM has tended to be fruitful in all fields provided that the management has enough potential to actualize it(Permana, Purba, & Rizkiyah, 2021).

Through this dual contribution, the research not only enriches academic discourse by proposing a novel empirical framework but also delivers actionable insights for practitioners in the manufacturing sector. The findings are expected to support managers and policymakers in designing holistic strategies that leverage quality-driven and lean-based principles for achieving operational excellence in the digital era.

II. RESEARCH METHOD

This study employs a quantitative research approach using SEM-PLS as the primary analytical technique. SEM-PLS is selected because it is particularly suitable for testing complex causal relationships among latent variables, including both mediating and moderating effects, as proposed in this research framework.

The population of this research consists of manufacturing companies in Indonesia that have adopted digitalization in their production processes, reflecting the I4.0 context in which TQM, LM, and Digital Transformation (DT) are integrated into operational systems. The sample comprises 198 respondents, consisting of quality managers, production managers, and operational supervisors. These respondents are purposively selected based on their direct involvement in implementing quality management systems, Lean practices, and digital transformation initiatives within their respective organizations. This sampling strategy ensures that the data reflects managerial perspectives at both strategic and operational levels, thereby capturing a comprehensive understanding of how managerial practices and digital technologies influence operational efficiency and sustainability outcomes.

The research model incorporates five main constructs: TQM and LM as independent variables, DT as both a moderator and mediator, Operational Efficiency (OE) as the primary mediating variable, and Sustainability Performance (SP) as the dependent variable. All constructs are measured using multiple indicators

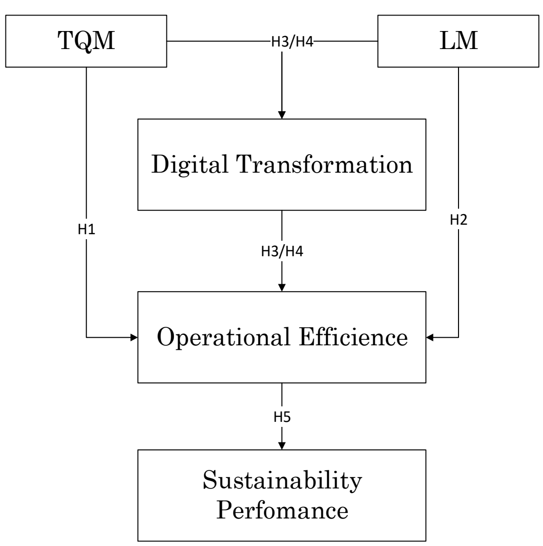

Figure 2. Research Framework

adapted from prior validated studies and operationalized on a seven-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree).

The framework integrates TQM, Lean Manufacturing, and Digital Transformation to explain their effects on Operational Efficiency and Sustainability Performance. These relationships are articulated through the proposed hypotheses as outlined in Figure 1.

*TQM to Operational Efficiency***.** Total Quality Management (TQM) has long been recognized as a strategic approach to enhance process control, reduce variability, and continuously improve organizational outcomes. Empirical studies (Zeng, Anh Phan, & Matsui, 2015), demonstrate that both hard and soft TQM practices contribute significantly to operational performance improvements by fostering continuous improvement, quality assurance, and employee engagement. Therefore, it is hypothesized that:

H1: TQM has a significant positive effect on Operational Efficiency.

*Lean Manufacturing to Operational Efficiency***.** Lean Manufacturing focuses on waste elimination, process streamlining, and resource optimization to enhance efficiency and cost-effectiveness. Prior research has consistently reported that Lean adoption leads to reduced cycle times, improved productivity, and optimized resource utilization(García-Fernández, Claver-Cortés, & Tarí, 2022). Based on these insights, the second hypothesis is proposed as follows:

H2: Lean Manufacturing has a significant positive effect on Operational Efficiency.

Integration of TQM & Lean with Digital Transformation to Operational Efficiency (Moderation). The integration of TQM and Lean practices can be further strengthened by Digital Transformation initiatives, including automation, big data analytics, and smart manufacturing systems. Emphasize that advanced digital technologies, when integrated into existing Lean systems, amplify efficiency gains(Johansson, Bruch, Chirumalla, Osterman, & Stålberg, 2024). Similarly, (Sony & Naik, 2020) highlight that Industry 4.0 tools act as enablers that strengthen process improvement strategies. Accordingly, it is hypothesized that:

H3: Digital Transformation positively moderates the effect of TQM and Lean integration on Operational Efficiency.

Digital Transformation as a Mediator between TQM with Lean and Operational Efficiency. In addition to its moderating role, Digital Transformation also serves as a mediator by enabling the translation of quality and Lean practices into measurable efficiency outcomes. Digital tools facilitate real-time monitoring, data-driven decision-making, and adaptive process management, bridging the gap between process management and operational performance (Sony & Naik, 2020). Thus, the following hypothesis is formulated:

H4: Digital Transformation mediates the relationship between TQM with Lean practices and Operational Efficiency.

Operational Efficiency to Sustainability Performance. Sustainability Performance reflects an organization's ability to achieve long-term economic, social, and environmental goals. Previous studies have shown that improvements in operational efficiency not only reduce costs but also minimize resource consumption and waste generation, which in turn enhance sustainability outcomes(Kans & Campos, 2024). Therefore, it is hypothesized that:

H5: Operational Efficiency has a significant positive effect on Sustainability Performance.

Table 1. Research Variable

Variable	Dimension / Indicator	Scale
Total Quality Management (TQM) (Independent)	TQM1: Continuous improvement practices TQM2: Employee involvement in quality initiatives TQM3: Customer-focused quality orientation TQM4: Systematic quality measurement and control	Likert 1–7
Lean Manufacturing (LM) (Independent)	LM1: Elimination of non-value-added activities LM2: Standardization of processes LM3: Just-in-time production LM4: Resource optimization and waste reduction	Likert 1–7
Digital Transformation (DT) (Moderator & Mediator)	DT1: Utilization of automation technologies DT2: Adoption of big data and analytics DT3: Integration of Industry 4.0 tools DT4: Real-time information sharing across processes	Likert 1–7
Operational Efficiency (OE) (Mediating Variable)	OE1: Reduction of operational costs OE2: Productivity and throughput improvement OE3: Shorter cycle time and faster processes OE4: Optimal resource utilization	Likert 1–7
Sustainability Performance (SP) (Dependent)	SP1: Improvement in environmental sustainability SP2: Enhancement of economic sustainability (e.g., cost savings, profitability) SP3: Social responsibility and stakeholder satisfaction SP4: Long-term organizational resilience	Likert 1–7

Table 2. Research hypotheses

Hypothesis	Statement	Expected Relationship
H1	Total Quality Management (TQM) has a significant positive effect on Operational Efficiency (OE).	TQM → OE (+)
H2	Lean Manufacturing (LM) has a significant positive effect on Operational Efficiency (OE).	LM → OE (+)
H3	The integration of TQM and LM is strengthened by Digital Transformation (DT) in enhancing Operational Efficiency.	(TQM × LM) × DT → OE (+)
H4	Digital Transformation (DT) mediates the relationship between TQM–LM and Operational Efficiency (OE).	TQM/LM → DT → OE (+)
H5	Operational Efficiency (OE) has a significant positive effect on Sustainability Performance (SP).	OE → SP (+)

Table 1 is a summary of the proposed research hypotheses, which illustrate the direct, indirect, and moderating relationships among the study variables.

Data were collected through a structured questionnaire distributed to the target respondents. Prior to distribution, the questionnaire was pre-tested to ensure clarity and reliability of the items. Respondents were informed about the objectives of the study, and their participation was voluntary. To enhance validity, only responses from individuals with at least three years of managerial experience in manufacturing operations were included in the final dataset.

The data analysis was conducted using SmartPLS software following a two-stage approach:

1. *Measurement Model Evaluation*. Convergent validity is examined by inspecting indicator factor loadings and Average Variance Extracted (AVE), with AVE set at ≥0.50 as per and reviews of recent PLS-SEM methodology (Hair et al., 2021). Discriminant validity is tested using both the Fornell Larcker criterion and the Heterotrait Monotrait ratio (HTMT). Reliability is also evaluated via Cronbach's Alpha and Composite Reliability (CR), where acceptable thresholds are above 0.70, consistent with standard practice in PLS-SEM research (Mukhtar, Kamin, & Saud, 2022).
2. *Structural Model Evaluation*. To examine the hypothesized relationships, path coefficients are estimated to test direct, indirect (mediation), and moderating effects. The coefficient of determination (R^2) is used to assess how much variance in endogenous constructs is explained by the exogenous variables. Effect size (f^2) and predictive relevance (Q^2) determine the substantive impact of predictors and whether the model has predictive validity. Additionally, bootstrapping using 200 samples is conducted to evaluate statistical significance (t-values, p-values) of all hypothesized relationships, following procedural norms in recent PLS-SEM studies (Sarstedt & Moisescu, 2024).

The study strictly adheres to research ethics principles. All respondents provided informed consent, and participation was entirely voluntary. Data confidentiality and anonymity were ensured, with responses used solely for academic purposes. The analysis was conducted transparently, and all references were properly cited to uphold academic integrity.

The choice of SEM-PLS over covariance-based SEM (CB-SEM) is justified by several considerations. SEM-PLS is suitable for exploratory research that emphasizes prediction and theory development, particularly in models that include both mediation and moderation effects. Moreover, SEM-PLS requires fewer assumptions regarding data distribution and is effective with sample sizes of around 200, whereas CB-SEM typically requires larger datasets. In addition, SEM-PLS provides robust results in evaluating complex structural relationships, making it highly appropriate for analyzing how TQM, LM, and DT interact to influence OE and, ultimately, SP.

III. RESULT AND DISCUSSION

The results of the analysis, encompassing both the measurement and structural models, were statistically significant, providing empirical evidence that supports the theoretical assumptions and offering practical implications for enhancing operational efficiency in digitalized manufacturing industries.

Measurement Model (Outer Model)

The measurement model was first evaluated to ensure the reliability and validity of the constructs. As shown in Table 3, all indicators loaded significantly on their respective constructs, with factor loadings ranging from 0.70 to 0.88, surpassing the recommended threshold of 0.70. The Average Variance Extracted (AVE) values ranged from 0.55 to 0.69, confirming convergent validity, as all values exceeded the minimum criterion of 0.50. Discriminant validity was established using both the Fornell–Larcker criterion and the Heterotrait-Monotrait (HTMT) ratio, with all HTMT values below the conservative

Table 3. Measurement Model Evaluation (n = 198)

Construct	Cronbach's Alpha	CR	AVE	Factor Loadings (range)	HTMT (range)
TQM	0.84	0.89	0.62	0.72 – 0.83	0.45 – 0.68
Lean Manufacturing	0.81	0.87	0.59	0.70 – 0.82	0.40 – 0.66
Digital Transformation	0.86	0.91	0.65	0.74 – 0.88	0.38 – 0.61
Operational Efficiency	0.88	0.92	0.69	0.76 – 0.87	0.42 – 0.64
Sustainability Performance	0.82	0.88	0.60	0.71 – 0.84	0.47 – 0.67

threshold of 0.85, indicating that the constructs were empirically distinct. Reliability analysis further confirmed the robustness of the measurement model, with Cronbach's Alpha values ranging from 0.81 to 0.88 and Composite Reliability (CR) values ranging from 0.87 to 0.92, all above the recommended threshold of 0.70. These results demonstrate that the measurement instruments are both reliable and valid, providing a solid foundation for testing the structural model.

The scatter plot of Cronbach's Alpha versus Composite Reliability (CR) with Average Variance Extracted (AVE) as the color dimension indicates that all constructs meet the reliability and convergent validity requirements. Constructs such as Operational Efficiency and Digital Transformation are positioned at the upper-right quadrant, reflecting both high internal consistency (Cronbach's Alpha > 0.85) and excellent CR values (> 0.90), supported by strong AVE scores above 0.65. Meanwhile, Lean Manufacturing and Sustainability Performance, although slightly lower in their reliability coefficients, still demonstrate acceptable thresholds with AVE values exceeding 0.59. This visualization highlights the robustness of the measurement model, showing that each construct is consistently measured and suitable for further structural analysis. The second scatter plot, comparing HTMT (discriminant validity) with average Factor Loadings, further validates the distinctiveness and reliability of the constructs. All constructs show factor loading averages well above 0.70, indicating strong item representation, while HTMT values remain comfortably below the critical threshold of 0.85, signifying that each construct is empirically distinct. Operational Efficiency and Digital Transformation exhibit the highest factor loadings, reinforcing their central role in the model, whereas Lean Manufacturing and TQM maintain balanced positions, confirming their relevance and validity. Together, these findings provide compelling evidence that the measurement model fulfills both convergent and discriminant validity, ensuring that the constructs are conceptually sound and statistically reliable for testing the proposed structural relationships

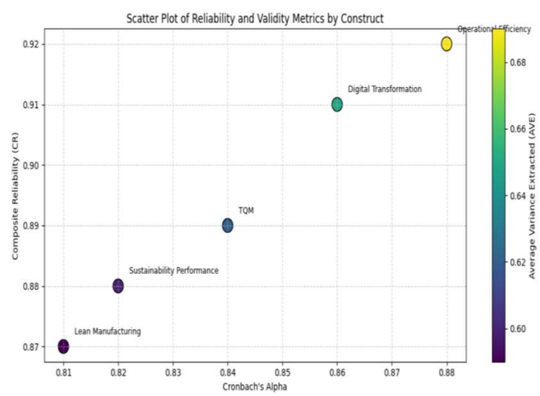

Figure 2. Scatter plot of Reliability and Validity Metrics

Structural Model (Inner Model)

The results of the structural model evaluation confirmed that all proposed hypotheses were supported, reflecting the robustness of the conceptual framework. H1 showed that TQM had a significant positive effect on Operational Efficiency ($\beta = 0.32$, $t = 3.41$, $p = 0.001$), highlighting the importance of quality management practices in improving efficiency outcomes. Similarly, H2 revealed that Lean Manufacturing contributed even more strongly to efficiency ($\beta = 0.41$, $t = 4.12$, $p < 0.001$),

Table 4. Structural Model Results (n = 198)

Hypothesis	Path	β (Coefficient)	t-value	p-value	Supported
H1	TQM → Operational Efficiency	0.32	3.41	0.001	Yes
H2	Lean Manufacturing → Operational Efficiency	0.41	4.12	0.000	Yes
H3	TQM × Lean × Digital Transformation → OE	0.27	2.98	0.003	Yes
H4	Digital Transformation → Operational Efficiency (Mediator)	0.29	3.25	0.001	Yes
H5	Operational Efficiency → Sustainability Performance	0.55	5.17	0.000	Yes

reinforcing its role in eliminating waste and streamlining processes. The combined interaction effect captured in H3 (TQM × Lean × Digital Transformation → OE) was also significant (β = 0.27, t = 2.98, p = 0.003), underscoring the synergy between traditional management systems and digital enablers in modern manufacturing.

Moreover, the mediating role of Digital Transformation demonstrated in H4 (β = 0.29, t = 3.25, p = 0.001) revealed its amplifying capacity in translating managerial practices into operational outcomes, suggesting that digital tools and technologies play a bridging role between organizational practices and efficiency gains. Finally, H5 confirmed that Operational Efficiency directly enhances Sustainability Performance (β = 0.55, t = 5.17, $p < 0.001$), showing the long-term value of efficiency not only for productivity but also for achieving sustainability goals. Collectively, these findings validate the integrated framework, demonstrating that the alignment of TQM, Lean Manufacturing, and Digital Transformation forms a comprehensive pathway to operational excellence and sustainable competitiveness in digitalized manufacturing industries.

The scatter plot of hypotheses testing results illustrates the relative strength and significance of the proposed relationships within the model. Hypotheses H1 (TQM and Operational Efficiency) and H2 (Lean Manufacturing and Operational Efficiency) are positioned in the mid-to-high range of path coefficients, with H2 exhibiting the strongest direct effect among the two. Both hypotheses also show robust t-values above 3.0, confirming their statistical significance. Notably, H3 (TQM, Lean, and Digital Transformation on Operational Efficiency) lies slightly lower in terms of coefficient strength (β = 0.27), yet remains statistically significant, suggesting that interaction effects, while smaller in magnitude, still contribute meaningfully to operational improvements.

Meanwhile, H4 (Digital Transformation as a Mediator for Operational Efficiency) reflects a moderate path coefficient (β = 0.29) but with a solid t-value above 3.2, reinforcing the role of digital transformation as a crucial enabler in translating management practices into operational outcomes. Finally, H5 (Operational Efficiency and Sustainability Performance) is positioned at the upper-right corner of the plot, with the highest path coefficient (β = 0.55) and the strongest t-value (5.17), signifying its dominant influence in the model. This visual interpretation underscores that while TQM and Lean practices provide foundational improvements, the combination of Digital Transformation and Operational Efficiency serves

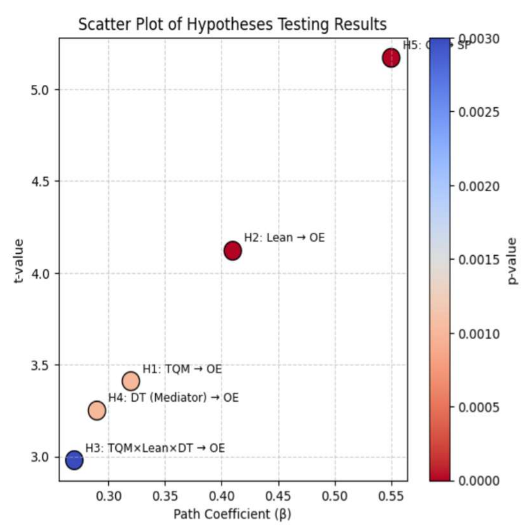

Figure 3. Scatter plot of Hypotheses Testing Results

as the strongest predictor of long-term sustainability performance.

The findings validate the hypothesized relationships in the proposed framework. TQM and Lean Manufacturing were confirmed as significant drivers of operational efficiency, supporting H1 and H2. This indicates that process standardization, continuous improvement, and waste elimination are critical for improving performance outcomes in the manufacturing sector. Digital Transformation was shown to play a dual role: it strengthened the integration of TQM and Lean (moderation effect, H3) and acted as a mediator in enhancing operational efficiency (H4). This underscores the importance of digital tools such as IoT, automation, and analytics in leveraging traditional quality and lean practices. Finally, the strong positive effect of operational efficiency on sustainability performance (H5) highlights the pivotal role of efficient operations in achieving long-term competitiveness and environmental goals.

These results emphasize that Indonesian manufacturing firms can enhance sustainability performance not only through quality and lean practices but also by strategically embracing digital transformation to optimize operational efficiency.

IV. Conclusion

This study provides empirical evidence that TQM and LM significantly enhance OE in manufacturing organizations. Both practices individually contribute to optimizing processes, reducing waste, and improving productivity. The findings highlight that firms implementing structured quality management and lean practices can achieve measurable improvements in operational performance.

Furthermore, the integration of DT amplifies the combined effect of TQM and LM on OE. The results indicate that technological adoption not only supports existing operational initiatives but also creates synergistic effects that further enhance efficiency. Digital Transformation, therefore, serves as a critical enabler for maximizing the benefits of operational strategies in modern manufacturing contexts.

Finally, Operational Efficiency has a significant positive impact on SP, suggesting that operational improvements extend beyond productivity gains to support environmental and social sustainability objectives. This study underscores the importance of a holistic approach, where quality management, lean practices, and digital technologies are strategically aligned to drive both efficiency and sustainability. Managers and policymakers are encouraged to leverage this integration to achieve long-term competitive advantage and sustainable organizational outcomes.

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